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*Research Article*

# Construction and Structural Analysis of Inter-Regional Industrial Circular Network: A Case of the Middle and Lower Reaches of the Yellow River in China

**Chong Yin**,[1,2] **Yingxin Cui**,[1] **Yue Liu**,[1] **and Xiaoni Su**[1]

[1]*Institute of Science and Technology for Development of Shandong, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250014, China*
[2]*Research Center of SCO Countries, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250353, China*

Correspondence should be addressed to Chong Yin; yc81@qlu.edu.cn

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Imbalance, incoordination, and inter-regional economic segmentation of the middle and lower reaches of the Yellow River (MLYR) have brought challenges to high-quality development in the Yellow River basin. To solve the problem, from the perspective of optimization of inter-regional economic circulation, combining input-output technology and complex network model, we proposed a systematic framework for structural analysis of circular economy and applied it in analysis of economic circulation of the MLYR. Firstly, we defined the inter-regional industrial circular network (ICN) and proposed the construction method of the ICN. Secondly, we designed indicators such as network, cycle, and inter-regional circulation effects to measure the structural characteristics of industrial circular network. Thirdly, the models and indicators were applied to explore the structural factors, revealing how the economic circulation was hindered and imbalance of development happened in the MLYR. We found that the external inter-regional circulation of the provinces was more differentiated, and limitation of utilization of technological resources and inter-regional capital flow, and weak investment and consumption demand for emerging services inhabited the quantity and vitality of cycles, which resulted in the imbalance of regional development in the MLYR. The results provide a basis for the suggestion, such as collaborative scientific and technological innovation, building a unified and efficient financial market, and development of emerging industries. The model and method were verified in the case of the MLYR and have practical meaning in supporting policy-making on promoting high-quality development of China.

## 1. Introduction

The Yellow River basin has a drainage area of over 752,000 sq km and covers seven provinces and two autonomous regions. Promoting the coordination of the relationships between sustainable growth, environmental protection, and resource conservation of the Yellow River basin is a strategic need to achieve high-quality development and narrow the development gap between the north and the south China, which concerns the great rejuvenation of the Chinese nation. To boost the high-quality development of the Yellow River basin, effective measures should be adopted to accelerate the transformation of driving forces and establish the modern industrial system with distinctive local features and advantages. The middle and lower reaches of the Yellow River (MLYR), including Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, span many important urban agglomerations and metropolitan areas such as the Central Plains and Shandong Peninsula, and the GDP of the MLYR in 2021 accounts for 74.91% of the whole basin [1]. However, due to natural factors such as the large east-west span of the Yellow River basin and the difference in resource endowments, the regions of the MLYR had great heterogeneity in economic growth, technological progress, and industrial structure [2]. GDP and population of Shandong were 4.05 times and 4.24 times that of Inner Mongolia, respectively [1], and R&D investment of Shandong was 7.72 times that of Shanxi, and Henan's was 5.36 times that of Inner Mongolia in 2021 [3]. Agriculture, animal husbandry, and mineral resource mining industries dominated the industrial economy of Inner Mongolia, Shanxi, and Shaanxi, which also took energy and mineral resource mining industries such as coal as the main body of economy, and Henan and Shandong were advantageous in manufacture and service sectors [4]. In 2021, the added value of Shanxi's coal industry increased by 11.2% over the previous year [5], the added value of Henan's traditional industries and high energy-consuming industries accounted for 48.4% and 38.3% of that of all the industries above designated size, respectively [6]. High energy-consumption, resource-consumption, and pollution were the features of the five provinces in the MLYR. In 2017, the total carbon emissions of the MLYR reached 79.80% of the whole basin [7]. Besides, the openness among regions was low, vitality of the market system was inhibited, there was a lack of economic exchanges, and coordination and circulation within the Yellow River basin were also weak [8, 9]. The imbalance, incoordination, and regional economic segmentation in the MLYR have brought severe challenges to high-quality economic development in the Yellow River basin.

Generally, circular economy refers to a model focusing on recycling, reusing, and reburnishing materials and resources [10]. The concept of "circular economy" is increasingly used when achieving environmental benefits and economic growth simultaneously. Circular economy focuses on the extension of material and resource circularity within the economic system in order to minimize the extraction of natural resources [11]. The main goal of development of circular economy is to build a resource-recycling industrial system and improve the efficiency of utilization of resources. When it comes to inter-regional coordinated development and adjustment of industrial system, industrial chains are important in supporting development of circular economy, of which the economic and technological relationships between the upstream and downstream make it possible to extend the industrial chain and promote the recycling of resources [12]. The essence of industrial chain is the technological relationships in inter-regional input-output economy, and the industrial circulation can be regarded as extension and feedback of industrial technological chains, on which the interlocked inner-regional and the inter-regional circulation system can be identified [13]. The problems in the MLYR are obviously reflected in the poor operation and circulation of the industrial system. How to describe the structure of circulation and then improve the structural effect of the inter-regional and interindustrial circular economy is the key to solving the problem of economic imbalance, incoordination, and segmentation in the MLYR.

Researches on circular economy mainly include two aspects. One is the approach of structural characteristics analysis on circular economy system, such as system dynamics (SD) and material flow analysis (MFA). SD focuses on modeling the dynamics of cost, revenue, and strategic and regulatory decisions and facilitating coping with increased complexity by enabling closed-loop thinking via identifying the causal structures underlying behavior and permitting to proactively experiment with the circular economy system through simulation [14, 15]. To support a circular plastics economy or a circular bioeconomy, some studies used quantitative uncertainties to conduct regional material flow analysis and geospatial mapping to identify local hotspots and circularity, and resource efficiency can be analyzed through a comprehensive set of indicators based on MFA [16, 17]. The other is the approach of evaluation of circular economy performance, such as data envelopment analysis (DEA) and econometric models. DEA such as slack-based, fully fuzzy, and closed-loop network models can be applied in evaluating input and output efficiencies, or investigating the performance of industrial circular economy systems, when taking recycling of resources in a system into account [18, 19]. Truncated regression and factor analysis integrated into DEA can measure the impact of selected indicators on circular efficiency [20, 21]. Besides, econometric estimation methods such as panel unit root tests, panel cointegration tests, and vector auto-regression, supplemented cluster analysis, can be used to estimate the main determinants of the circular economy and help to evaluate the efficiency of resource productivity [22]. These achievements provided many valuable references on the flow of physical materials, the impact of specific factors on the circular economy, and the evaluation of circular performance. However, limitations in analyzing the two-way interaction of value flows and impacts of comprehensive technological and economic factors across regions and industries, and exploring the inter-regional and interindustrial structure effects of economic circulation were obvious in the above empirical evidences. Input-output (I-O) models were then considered a useful tool for in-depth analysis of internal relationships and effects of industrial economic circulation and interdependencies among regions and industries [23]. Physical input-output table (PIOT) model can capture the interindustrial physical interactions of waste flows in the region [24]. I-O model can be applied to examine resource efficiency and circularity and compare recycling and nonrecycling scenarios in sectors [25]. Based on multiregion input-output models, inter-regional circular capability can be measured on multiplier, spillover, and feedback effects [26], and interindustrial circular capability can be measured on indicators such as internal circular rate, external circular rate, and chain expansion degree [27]. By integrating the two factors of natural resources and environment into the classical I-O table, physical and value input-output tables of circular economy can be established, respectively, and make a comparative analysis of the efficiency of circular economy in various sectors [28]. Improved influence and sensitivity coefficients were also used to measure participation of industrial sectors in the "dual circulation" of the value chain and structure upgrading effect [29]. However, although the classic input-output model can give a clear quantitative description of the relationships among industries, the information obtained through input-output analysis is too scattered, and it is difficult to fully present the complete structure of industrial system and structural features [30].

Complex networks have been widely used in the research of social and economic issues, including capturing the elastic characteristics of traffic network [31], analyzing the robustness and topological characteristics of urban road networks [32, 33], improving the efficiency of urban transportation system [34], and employing the topological indices arising from complex network theory to quantitatively analyze the transformation of user behavior pattern of bike sharing [35]. By abstracting each action subject and their inter-relationships in a complex network system into nodes and ties, network analysis can more comprehensively describe the whole structural characteristics of the network and the relationship between the subjects in the network [36]. Generally speaking, industrial network is a complex network with industrial sectors as nodes, and the edges reflect the extensive and intimate technical and economic relationships among industrial sectors in economic activities [37, 38]. By using the statistical method such as the Weaver-Thomas index to find the critical vector, filtering and mining information, restructuring the relationships, and projecting the foundational structure of economic system, the problem of redundancy and dispersion of information in I-O model can be solved [39]. Circular structure describes the circular relationships among industries and is an important subgraph in the industrial network [40]. Taking a cycle as the basic element of circular economy structure, Chen and Xiao [41] pointed out that the simplest industrial cycle is a two-way connecting path among two industries, and the more complicated cycle is composed of three or more industries, which is shown as "cycle" on the network diagram. The industrial network involves various feedback loops in its structure, and all the feedback loops exist on branches with relatively high reliability [42]. He also proposed that cycle degree is an important indicator to measure the ability of industries to participate in circulation and depict key industries. Indicators such as cycle length distribution, average cycle correlation, influence of the industrial cycle, and interactions of the weighted cycle can be used in analyzing industrial circulation structure [43]. The industrial fluctuations transmitted through the sector network can be fed back to the original industry, and the average of the shortest path and the longest path among industries can reflect the strength of industrial feedback loops in the sector network [44]. Giscard and Wilson [45] measured cycle centrality and subgraph centrality; that is, the proportion of the network flow intercepted by any selected node group and showed that the two indicators are more sensitive to identification of key network functions than the previous group centrality on two real networks. Circular network is an industrial circulation structure that reflects influence of circular linkage at the correlation of edges, which can provide new ideas for the in-depth study of the evolution characteristics and effects of structure of inter-regional industrial economy. At present, few researches referred to the construction of industrial circular network, and the projection methods were insufficient. Besides, the current indicators of industrial circular structure were incomplete and unsystematic.

The imbalance, incoordination, and inter-regional economic segmentation of the MLYR have brought about the crisis of energy, resource, and environment in Yellow River basin, and even can hinder the high-quality development of China. Improving the capacity of industrial circular economy of the MLYR is an important path to solve the problems. However, the existing research methods were insufficient in analysis of inter-regional and interindustrial structures of circular economy. Therefore, based on integration of I-O model and the industrial complex network method, we proposed a systematic framework for structural analysis of circular economy, including the modeling of industrial circular network and the indicators of circular structure, which contributed to describing the structure and measuring the effects of circular economy among regions and industries. According to the input-output tables for 2012 and 2017, we conducted an empirical analysis on the MLYR based on construction and structural analysis of inter-regional industrial circular network, to explore the structural factors restricting the development of circular economy in the MLYR, and the effectiveness and practical significance of models and methods were verified.

The organizational structure of this paper is as follows. Section 2 is models and methods of inter-regional industrial circular network (ICN), including the definition and construction method of the ICN, the indicators such as network, cycle, and inter-regional circulation effects to measure the structural characteristics of industrial circular network. Section 3 is the empirical analysis of the inter-regional industrial circular network structure of the MLYR, revealing how the economic circulation was hindered and imbalance of development happened in the MLYR. Section 4 is the conclusion and suggestions.

## 2. Models and Methods of Inter-Regional Industrial Circular Network

*2.1. Inter-Regional Industrial Circular Network Model.* The nonzero industrial technological correlation coefficient between two industries does not necessarily indicate an effective interindustry relationship but requires that the technological correlation coefficient among the industries exceeds a certain critical value to form an effective economic relationship among the two industrial sectors, that is, an industrial chain. Technological correlation coefficients can be filtered according to Weaver-Thomas index, and the filtered coefficient matrix can be further mapped into a 0-1 adjacency matrix. Based on this adjacency matrix, the inter-regional industrial network (IRIN) is constructed. The IRIN is a complex system with industrial sectors as nodes and intersectoral technological linkages as edges. The weight of the edges can be measured by inter-regional industrial technology correlation (IRITC), with reference to Yin et al. [46]. So the IRIN is a backbone model of a real multiregional composite economic industrial system composed of multiple regional economic industrial subsystems. The whole network constitutes the system of industrial chains inside and outside the regions, which depicts the industrial structure of the economic system among specific regions [39]. The input, transfer, transformation, and output of resources are carried out along industrial chains. At the same time, the stepwise increasing value flow is transmitted along the industrial chains, and the end-to-end industrial chain (cyclic chain) can bring sustainable, stable, and efficient resource transformation and utilization and value increment of circular economy [39]. The inter-regional industrial circular network (ICN) is formed by the aggregation of all circular industrial chains, and it is a systematic structural model of the real multiregional macroeconomic circular system. In the IRIN, a closed path that takes its any node as the starting node, passes through the nonrepeating nodes along the nonrepeating edges, and then returns to the starting node, is defined as the industrial cycle (referred to as cycle). If a cycle contains $p$ nodes, it is called $p$-order cycle. The closed path starting from its any node, traveling the nonrepeating edges once and only once, and then returning to the starting node in the IRIN is defined as the ICN, which is abstracted as a graph ICN $= (V, E, W)$ composed of a node set $V$, an edge set $E$, and a weight set $W$. Because of the effectiveness of the complex industry network in depicting the actual multiregional economic system and its high ability to explore the economic structure and momentum profits [44, 47], the ICN can be constructed on the IRIN to reveal the core structural mechanism of the sustainable economic development and structural evolution, and dynamics of the multiregional economic system. The ICN is a subnetwork with the most nodes formed by the merger and nesting of industrial cycles, in which the in-degree of any node is equal to its out-degree, and the ICN is an Euler graph in essence [48]. The cycle and the ICN are relatively independent circular subnetwork of the IRIN, describing the industrial trajectory and dynamic feedback function of economic growth, and contain the closed industrial chains and industrial functional circular subgroups. More complex the ICN is, richer the ways and paths of technology and economic circulation are.

The construction method of inter-regional industrial circular network is as follows:

(1) The inter-regional industrial technology correlation coefficient matrix $G$ reflects the technological correlation between industry $i$ in region $r$ and industry $j$ in region $s$ under the influence of policy and market competition. The IRITC is to measure the industrial technological correlation among the industrial sectors of the regions, which refers to the probability of linkage. The element of $G$ is

$$
\begin{aligned}
G(ri, sj) &= \frac{CS_i^r CS_i^s}{|CS_i^r||CS_i^s|} \frac{TS_j^r TS_j^s}{|TS_j^r||TS_j^s|} \frac{\left[f_{i,j}^r G(ri, rj) + f_{i,j}^s G(si, sj)\right]}{\left(|M^r - M^s| + 1\right)\left(|P^r - P^s| + 1\right)},\\
F_{i,j}^r &= \frac{P^r}{P^s} \frac{M^r}{M^s} \frac{ZT_i^r}{ZT_i^r + ZT_i^s},\\
F_{i,j}^s &= \frac{P^s}{P^r} \frac{M^s}{M^r} \frac{ZC_j^s}{ZC_j^r + ZC_j^s},\\
f_{i,j}^r &= \frac{F_{i,j}^r}{F_{i,j}^r + F_{i,j}^s},\\
f_{i,j}^s &= \frac{F_{i,j}^s}{F_{i,j}^r + F_{i,j}^s},
\end{aligned}
\tag{1}
$$

where $CS_i^r$ is the $i$-th line of direct consumption coefficient matrix, which represents the direct consumption of the $i$-th sector product by each sector in region $r$. $TS_j^r$ is the $j$-th column of direct consumption coefficient matrix, which represents the direct consumption of each sector product by the sector $j$ in region $r$. $P^r$ is the policy parameter (local fiscal expenditure/gross domestic product) in region $r$, $M^r$ is the market parameter in region $r$, $ZT_i^r$ is the intermediate input of sector $i$ in region $r$, and $ZC_j^s$ is the intermediate output of sector $j$ in region $s$. The direct consumption coefficient in input-output model can be directly used as the measurement of inner-regional industrial technology correlation, that is, $G(si, sj)$ and $G(si, sj)$. The matrix of IRITC including $m$ regions and $n$ industrial sectors is shown in Table 1. $G$ is the matrix of $mn$ rows and $mn$ columns. $G(ri, rj)$ is the $y$-th row and $z$-th column element of the matrix, where $y = [(r-1) \times n + i]$ and $z = [(s-1) \times n + j]$.

Table 1: Inter-regional industrial technology correlation (IRITC) matrix ($mn \times mn$).

| | | Region 1 | | | ... | Region $m$ | | |
|---|---|---|---|---|---|---|---|---|
| | | Sector 1 | ... | Sector $n$ | ... | Sector 1 | ... | Sector $n$ |
| Region 1 | Sector 1 | | | | | | | |
| | ... | | | | | | | |
| | Sector $n$ | | | | | | | |
| ... | ... | | | | | | | |
| Region $m$ | Sector 1 | | | | | | | |
| | ... | | | | | | | |
| | Sector $n$ | | | | | | | |

(2) Based on the Weaver-Thomas index, the $mn$ critical values $\alpha_1, \alpha_2, \alpha_3, \ldots, \alpha_{mn}$ corresponding to the $mn$ columns are determined from the column entries of $G$, where $m$ is the number of regions and $n$ is the number of industries in region $m$. Weaver-Thomas index is

$$w(ri, sj) = \sum_{i=1}^{n} \left[ z(b, ri) - 100 \times \frac{G(b, sj)}{\sum_{d=1}^{mn} G(d, sj)} \right]^2, \quad (2)$$

where

$$z(b, ri) = \begin{cases} \dfrac{100}{[(r-1) \times n + i]}, & b \le [(r-1) \times n + i], \\ 0, & b > [(r-1) \times n + i]. \end{cases} \quad (3)$$

The critical value is $\alpha_{sj} = \min\{w(1, sj), w(2, sj), \ldots, w(mn, sj)\}$ $(sr, s = 1, 2, \ldots, m,\ i, j = 1, 2, \ldots, n)$.

(3) According to the matrix G, the adjacency matrix $A$ of the IRIN is constructed, as shown in the following formula (8):

$$A(ri, sj) = \begin{cases} 1, & G(ri, sj) \ge \alpha_{sj}, \\ 0, & G(ri, sj) < \alpha_{sj}, \end{cases} \quad (4)$$

where $A(ri, sj) = 1$ indicates that sector $i$ and sector $j$ have the associated edges and the weight of the edge is the IRITC.

(4) According to the adjacency matrix $A$ of the IRIN, the initial structure matrix $U(0) = [u_{i,j}(0)]$, $u_{i,j}(0) = a_{i,j}$, and initial indication matrix $S(0) = [s_{ij}(0)]$, $s_{ij}(0) = j$ are established.

(5) All the cycles $C = \{C_1, C_2, .., C_p\}$ are identified in the IRIN based on iterative optimization of the structure matrix and indication matrix. When $i = j$ and $u_{ij}(t) = 1$, the directed cycle is identified based on searching of path; that is, a cycle $C_1 = v_i v_1, \ldots, v_j v_i$ is obtained by recording and outputting the sequence number of the previous node of the currently searched path through the indication matrix. The iteration formula is as follows:

$$u_{ij}(t) = \max\left\{ u_{ij}(t-1),\ u_{\mathrm{it}}(t-1) \cdot u_{tj}(t-1), \right\},$$
$$s_{ij}(t) = \begin{cases} s_{ij}(t-1), & \text{if } u_{ij}(t-1) \ge u_{\mathrm{it}}(t-1) \cdot u_{tj}(t-1), \\ s_{\mathrm{it}}(t-1), & \text{if } u_{ij}(t-1) < u_{\mathrm{it}}(t-1) \cdot u_{tj}(t-1), \end{cases} \quad (5)$$

where $t = 1, 2, \ldots, mn$ ($mn$ is the number of all the sector nodes in the $m$ regions and $1 \le i, j \le mn$).

(6) All the cycles are sorted according to the weight from high to low, set the empty sets $T_1, T_2 \ldots$, and add the first cycle to $T_1$. According to whether the next cycle has a common node with the existing set, the cycle is added to the set in the following cases, as shown in Figure 1. Gray cycles and dotted lines represent common nodes or edges.

(7) When all the cycles have entered the relevant set, several nonempty sets are formed at this time. Any of the nonempty set is an independent subnetwork. The subnetwork with the largest number of nodes is the ICN, which contains the cycle set $C = \{C_1, C_2, .., C_f\}$.

*2.2. Statistics of Inter-Regional Industrial Circular Network Structure*

*2.2.1. Network Circulation Effect.* This indicators measure the circular structure effect of the ICN and its circular status in the IRIN.

(1) Circulation correlation level (CL). The circulation correlation level refers to the weight proportion of the circular network in the industrial network, which measures the circulation of the ICN in the IRIN, as shown in equation (6). The larger the value is, the deeper the circular capability of the network is.

$$CL = \frac{W_{\mathrm{ICN}}}{W_{\mathrm{IRIN}}}, \quad (6)$$

where $W_{\mathrm{ICN}}$ is the total weight of the ICN, and $W_{\mathrm{IRIN}}$ is the total weight of the IRIN.

(2) Technical circulation capacity (TC). The technical circulation capacity ($TC$) refers to the circulation effect of the total R&D investment on all the industrial edges in all the cycles of the circular network, which depicts the quality and vitality in the ICN, as shown in equation (7). The higher the value is, the higher the quality of circular economy is.

$$TC = \frac{\sum_i RD_i}{\sum [N(l) \times l]}, \quad (7)$$

where $RD_i$ is the R&D investment of industrial sector $i$, the cycle length $l$ is defined as the quantity of edges

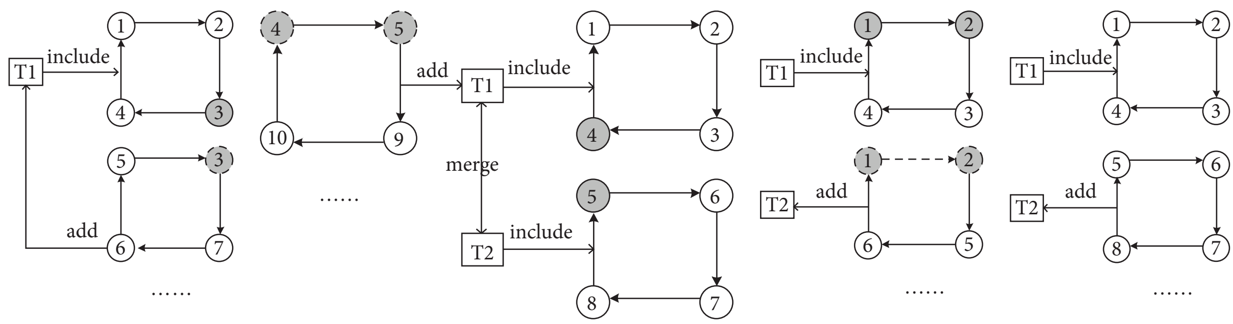



Figure 1: Several situations of whether there are common nodes between new cycles and sets: (a) the case that a new cycle has a common node and no common edge with an existing set; (b) the case that a new cycle has a common node and no common edge with existing sets; (c) the case that a new cycle has a common node and a common edge with an existing set; (d) the case that there is no common node between a new cycle and all existing sets.

contained in a cycle, and $N(l)$ denotes the quantity of industrial cycles whose cycle length is $l$ in the ICN.

(3) Base circularity (BC). The number of industrial cycles can describe scope of the circular industrial linkages in the network structure [49]. The base circularity is the quantity of cycles identified in the ICN and is recorded as $BC$, as shown in equation (8). The larger the value is, the stronger the basic circular capability of circular economy is.

$$BC = N(f), \tag{8}$$

where $f$ is the sequence number of the cycle in the ICN.

(4) Internal circulation degree (IC) and external circulation degree (EC). If a cycle in the ICN contains the industrial sectors from $x$ provinces, we call it the level-$x$ cycle. The internal circulation degree and the external circulation degree are the proportion of the number of industrial cycles within the province and between provinces to the total number of industrial cycles, respectively, as shown in equations (9) and (10). The higher the value is, the higher the status and role of this level cycle in the network are.

$$IC = \frac{N(Z_1)}{N(f)}, \tag{9}$$

where $N(Z_1)$ represents the number of level-1 cycles.

$$EC(x) = \frac{N(Z_x)}{N(f)}, \tag{10}$$

where $N(Z_x)$ represents the number of level-$x$ cycles.

*2.2.2. Cycle Circulation Effect.* These indicators measure the circular structure characteristics, status, and functions of the industrial cycles.

(1) Cycle length and relative frequency. The cycle length distribution of industrial sectors describes the number of industrial cycles of each length [40]. On this basis, we use relative values to reflect the status of industrial cycles of each length. The proportion of industrial cycles with cycle length equaling to $l$ in all the industrial cycles is defined as CF($l$), as shown in equation (11). The larger the proportion is, the greater the circular capability of the cycles of this length is.

$$CF(l) = \frac{N(l)}{\sum N(l)}, \tag{11}$$

where $N(l)$ is the number of industrial cycles with cycle length of $l$ in the ICN.

(2) Average relative investment. The average relative investment refers to the average relative R&D investment carried by each industrial cycle of different cycle lengths, which describes the relative investment level to induce the efficient circulation by technological innovation, as shown in equation (12). The larger the value is, the stronger the sustainable circulation vitality of industrial technological innovation in the cycles of this length is.

$$AI(l) = \frac{\sum_{f=1,L(f)=l}^{BC} rd(f)}{N(l)}, \tag{12}$$

where $rd(f)$ is the proportion of R&D investment of the cycle $f$ in the total R&D investment of all the industries in ICN, and $L(f)$ is the length of the industrial cycle.

(3) Cycle centrality. The centrality for individual cycles is based on the premise that a cycle is central if it intersects an important proportion of information [50]. Combinatorically, the problem of counting all the walks visiting at least one vertex of a cycle is the graph-theoretic equivalent of counting the integer multiples of a prime number. This framework notably provides an exact formula for the total number of closed walks on the graph which intersect the cycle $f$ [51].

Asymptotically, this formula produces a single real number between 0 and 1, a fraction, representing the proportion of cycles intersecting the cycle $f$, as shown in equation (13). The cycle centrality is used as a marker of structural cycle importance in networks, describing the status and influence of functional cycles.

$$C(f) = \det\left[1 - \frac{1}{\eta} B_{ICN/f}\right], \tag{13}$$

where det denotes the determinant, $B$ is the adjacency matrix of ICN, and $\eta$ is the maximum eigenvalue corresponding to $B$. $B_{\mathrm{ICN}/f}$ is the residual matrix in matrix $B$ after eliminating all the matrix elements corresponding to all the edges accessed by the cycle $f$.

(4) Average cycle centrality. The average cycle centrality refers to the role and influence of each industrial cycle of different cycle lengths in the network, as shown in equation (14). The larger the value is, the stronger the leading and driving role of the cycles of this length in the network is.

$$AD(l) = \frac{\sum_{f=1,L(f)=l}^{BC} C(f)}{N(l)}. \tag{14}$$

*2.2.3. Inter-Regional Circulation Effect.* These indicators measure the impact of industrial technological innovation activities in one region on other regions in the process of economic circulation in the ICN.

Technology spillover and technology absorption reflect the technology diffusion activities of sectors from the perspective of economy outflow and inflow, respectively [52]. The total technology flow matrix, including absorption flow matrix $T_f$ and spillover matrix $T_b$, is

$$\begin{aligned} T &= \widehat{rd}(\widehat{x})^{-1}(I - M_{ICN})^{-1} + (I - M_{ICN})^{-1}\widehat{rd}(\widehat{x})^{-1} \\ &= T_f + T_b, \end{aligned} \tag{15}$$

where $\widehat{x}$ is the diagonal matrix of total output of industrial sectors, and $\widehat{rd}$ is the diagonal matrix of industrial R&D investment. $M_{\mathrm{ICN}}$ is the weight matrix of the ICN.

(1) Inter-regional technology spillover intensity. Inter-regional technology spillover intensity (IRTSI) is the sum of technology flows overflowed from region $r$ to region $s$ in the ICN, as shown in equation (16). The higher the value is, the greater the spillover effect of technological economic circulation is.

$$IRTSI_{r,s} = \sum_{i=(r-1)n+1}^{rn} \sum_{j=(s-1)n+1}^{sn} T_{i,j}. \tag{16}$$

(2) Inter-regional technology absorption intensity. Inter-regional technology absorption intensity (IRTAI) is the sum of the feedback technology flows received by region $s$ from region $r$ in the ICN, as shown in equation (17). The higher the value is, the greater the absorption effect of technological economic circulation is.

$$\mathrm{IRTAI}_{s,r} = \sum_{i=(s-1)n+1}^{sn} \sum_{j=(r-1)n+1}^{rn} T_{i,j}, \tag{17}$$

where $r, s = 1, 2, \ldots, m$, $r < s$, and $n$ is the number of industrial sectors in region $r$ or region $s$.

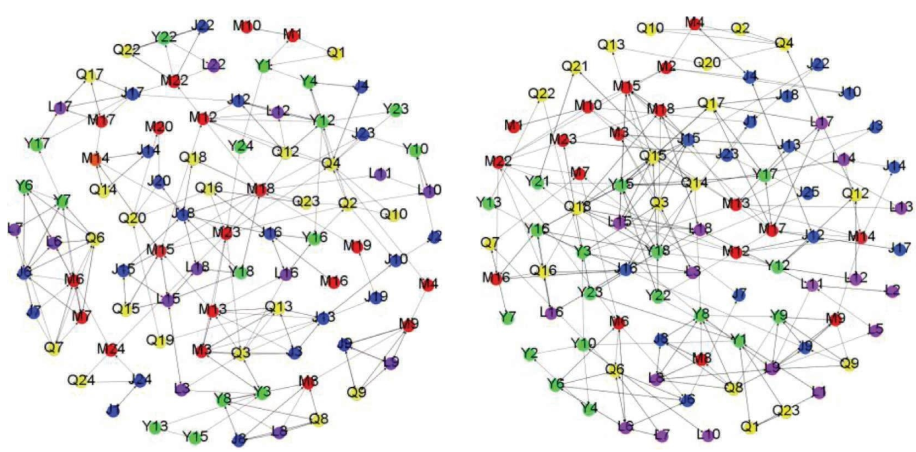
## 3. Analysis of the Inter-Regional Industrial Circular Network Structure of the MLYR

*3.1. Data Sources and Network Construction.* (a) The provincial input-output tables of Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong in the MLYR of China for 2012 and 2017 were applied (https://www.stats.gov.cn/). The period from 2012 to 2017 is just in the economic fluctuation cycle of China and is of great value in structural analysis, and the input-output data can just reflect the typical changes in this period. To cope with the dilemma of economic growth after the financial crisis in 2008, from 2012 to 2017, China intensively issued many very important policies, such as "innovation-driven development strategy" in 2012, "mass entrepreneurship and innovation" in 2015, "supply-side structural reform" in 2016, "rural revitalization strategy" in 2017, which had deeply changed the economic and industrial structure, the level of investment and consumption, and supply-demand relationships, which promoted technological progress. The changes are necessary implied in the input-output tables, and the iteration of technical coefficient matrix can indicate the changes of economic and industrial structure from 2012 to 2017 and the impact of environment of system. Besides, referred to related literatures [53, 54], we cautiously modified the input-output coefficient by integrating the investment of R&D on industry sectors into the input-output model, which fully absorbed the impact of technical fluctuations from 2012 to 2017, so that the data can better reflect the dynamic relationship of this period, and the evolution trend of the regional industrial circular network can be fully displayed. 42 sectors were merged into 25 sectors, as shown in Table 2, with a total of 125 sector nodes. (b) The competition of market of the MLYR was measured by the marketization index of the provinces for 2012 and 2017 [55]. (c) Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong were abbreviated as $M$, $Q$, $J$, $Y$, and $L$, respectively, in the network. For example, "$L1$" indicates the sector node of Mining and Washing of Coal in Shandong. MATLAB was used to process the data, and ARCMAP and GEPHI were used for visualization. The industrial sector nodes of $M$, $Q$, $J$, $Y$, and $L$ were depicted with yellow, blue, red, purple, and green solid circles, respectively.

The ICN of the MLYR in 2012 and 2017 was extracted as shown in Figure 2. The numbers of edges in the ICNs were 302 in 2017 and 293 in 2012. The functionalities, such as connectivity and communication capability of complex networks, are related to the number of paths between node

Table 2: Industrial sector classification and number.

| No. | Industrial sector |
|---|---|
| 1 | Mining and washing of coal |
| 2 | Extraction of crude petroleum and natural gas |
| 3 | Mining of metal ores |
| 4 | Mining and quarrying of nonmetallic mineral and other mineral |
| 5 | Manufacture of food and tobacco |
| 6 | Manufacture of textiles |
| 7 | Manufacture of textile wearing apparel, footwear, leather, fur, feather, and its products |
| 8 | Processing of timbers and manufacture of furniture |
| 9 | Papermaking, printing and manufacture of articles for culture, education, and sports activities |
| 10 | Manufacture of refined petroleum, coke products, processing of nuclear fuel |
| 11 | Manufacture of chemical raw materials and chemical products |
| 12 | Manufacture of nonmetallic mineral products |
| 13 | Manufacture and processing of metals |
| 14 | Manufacture of fabricated metal products, except machinery and equipment |
| 15 | Manufacture of general-purpose machinery |
| 16 | Manufacture of special-purpose machinery |
| 17 | Manufacture of transport equipment |
| 18 | Manufacture of electrical machinery and apparatus |
| 19 | Manufacture of communication equipment, computer, and other electronic equipment |
| 20 | Manufacture of measuring instruments |
| 21 | Other manufacture and comprehensive utilization of waste |
| 22 | Repair of fabricated metal products, machinery, and equipment |
| 23 | Production and supply of electricity and steam |
| 24 | Production and distribution of gas |
| 25 | Production and distribution of water |



(a) (b)

Figure 2: The ICNs of the MLYR in 2012 and 2017. (a) 2012. (b) 2017.

Table 3: The network circulation effect of the ICN in the MLYR.

| Indicators | CL | TC | BC | IC (%) | EC | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Level-2 (%) | Level-3 (%) | Level-4 (%) | Level-5 (%) |
| 2012 | 0.26 | 164.94 | 6210 | 1.42 | 17.00 | 31.01 | 32.69 | 17.87 |
| 2017 | 0.28 | 264.65 | 7028 | 2.45 | 17.73 | 39.70 | 32.19 | 7.94 |

pairs in the networks, and more edges mean stronger robustness of the network [56, 57]. Thus, the increase in the number of edges indicated that the complexity of the circular network was higher, and the circular correlation among industries was stronger. The ICN included 89 sector nodes in 2012 and 91 sector nodes in 2017, including 20 nodes in Shaanxi, 18 nodes in Inner Mongolia, 18 nodes in Shanxi, 18 nodes in Henan, and 17 nodes in Shandong. The number of nodes in Inner Mongolia, Shaanxi, and Shanxi decreased slightly, while the number of nodes in Henan and Shandong increased, indicating that the degree of circular participation of each province is more balanced, and the level of circular

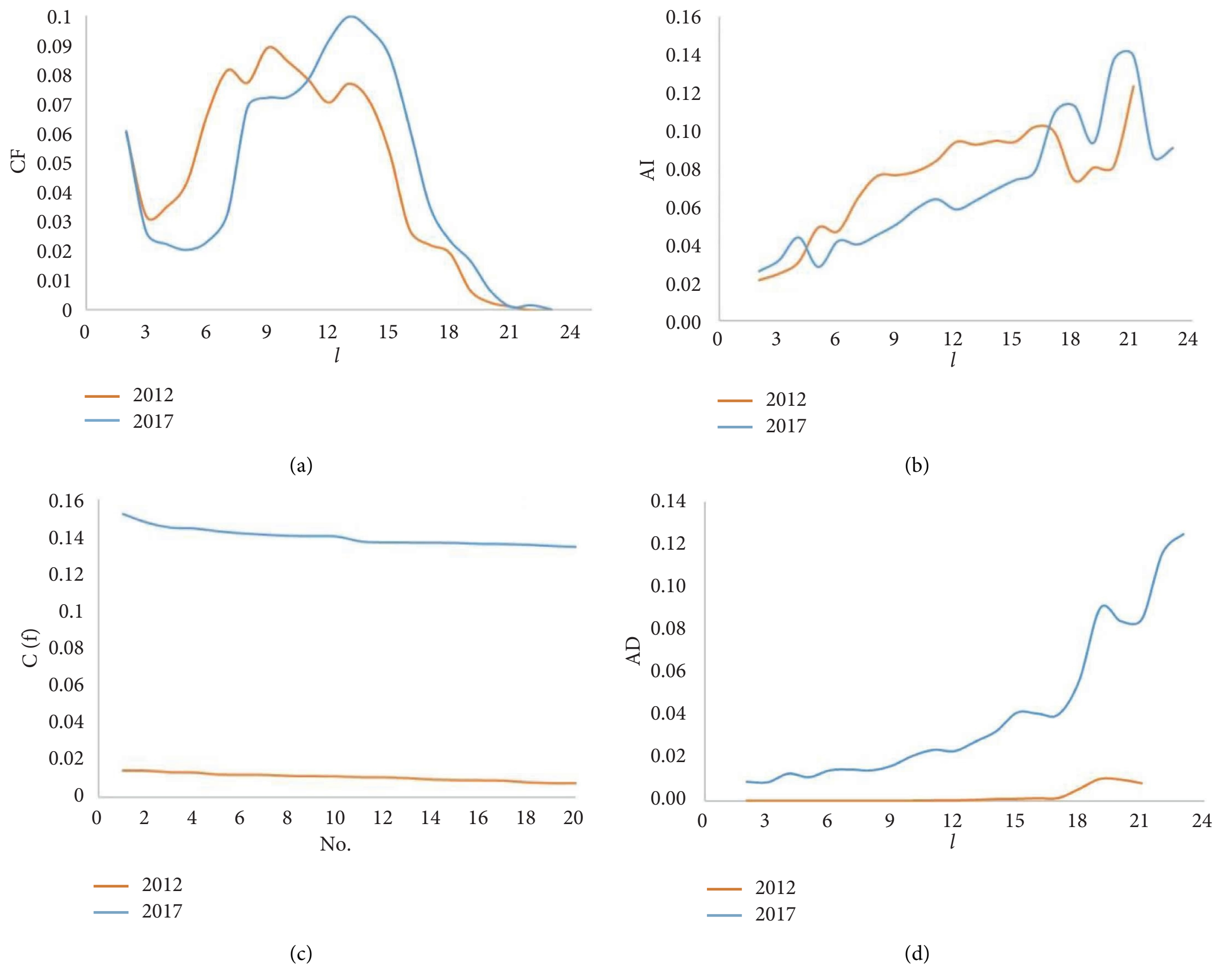



Figure 3: The cycle circulation effect in 2012 and 2017. (a) Cycle length and relative frequency (CF), (b) average relative investment (AI), (c) cycle centrality (C(f)), and (d) average cycle centrality (AD).

correlation of industries among the regions had also increased. Shaanxi had the largest number of industrial nodes in the ICN, played an important role in the industrial circulation, and was in a leading position in promoting construction of industrial technology and economic circulation system in the MLYR. In addition, as an important field of supply-side structural reform in China and technological innovation-driven development, capability of manufacturing industries in the industrial circulation of the MLYR, such as industries 7–10, 12-13, 15–18, had been greatly improved, and those sectors gradually became the main body of the complex system of industrial circulation.

*3.2. Analysis of Network Circulation Effect.* Table 3 shows the network circulation effects of the ICN in the MLYR. The results and discussions are as follows. (a) The scope of interregional and interindustrial circulation was greatly expanded. As the economy could be described as a web of smaller circular economies where the core development depended on active participation of territorial stakeholders [58], the increase of CL indicates that the circular correlation among industries was enhanced, and the technological and economic interaction and feedback of related industries among the regions in the MLYR were improved. Specifically, Shandong and Shanxi deepened strategic industrial relationship and carried out multidimensional coordination in energy, transportation, industry, agriculture, trade, logistics, and other fields, and Shaanxi and Inner Mongolia began jointly promoted the development of modern agriculture and strengthened the connection of production and trade of agricultural products. It can be seen that driven by the government, local regional market channels were gradually opened, and this was the key reason for the increase of overall circulation. (b) The quality of circular economy had been effectively improved. The TC of the ICN in 2017 was more than 1.6 times that of 2012, indicating that technological innovation had injected strong vitality into the circular economy. The activities of industry-university-research cooperative innovation and technology transformation in the fields of chemical industry, food, and papermaking technology in Shandong and Shaanxi were obviously more active. Compared with the previous research result [59], it can be seen that the benefits of circular economy in the MLYR were directly associated with environmental protection, increased competitiveness, and innovation and technological research. (c) The growth capability of circular economy had been enhanced. The BC in 2017 was 1.13 times that in 2012. As industrial chain relationship management and sustainable industrial chain design played an important role in improving the growth of circular economy [60], the basic circular support ability was stronger in the MLYR. From 2015, Shandong and Henan encouraged mass entrepreneurship and innovation, Henan focuses on cultivating the new energy industries, and new technologies, industries, formats, and modes continued to flourish in some regions of the MLYR, which effectively increased participation of various economic and social subjects in circular economy of the MLYR. (d) The effect of internal circulation within regions was strengthened, and the effect of external circulation was reorganized. The IC increased and the EC changed unevenly in the period. In 2017, industrial internal circulation was highly improved, and the external circulation among three provinces was considerably improved and had become the dominant mode of industrial circulation in the MLYR, and the external circulation among three more regions was weaken. The construction and extension of the internal and external industrial circular chains can be promoted through structural reform and incentives on demand and supply sides [27], and under the interaction of multiple policies, the enhanced internal circulation was related to the integrated supply chains, reducing costs of production and interaction. On the other hand, under the effect of financial deleveraging and reducing systemic risks, the inter-regional capital flow and investment activities were restrained in some degree, which resulted in fluctuation of circulation effects among multiregions.

*3.3. Analysis of Cycle Circulation Effect.* The cycle circulation effects of the ICN in MLYR are shown in Figure 3, and the results and discussion are as follows. (a) The high-order cycles ($\text{cycle length} \in [15, 23]$) in the ICN with the greatest vitality and impact on inter-regional economic cooperation and product trade were composed of the interprovincial circular industrial chains, and its quantity, vitality, and impact had increased considerably. The CF of high-order cycles was improved to a certain extent, which was related to the changes of level-2 and level-3 cycles of the circular economy. Especially, the number of cycles of Shaanxi-Henan, Inner Mongolia-Shaanxi-Henan, and Inner Mongolia-Shaanxi-Shandong had increased. The AI and the AD of the high-order cycles showed a fluctuating upward trend, indicating that the inter-regional industrial circulation chain continued to grow harder, and the economic relevance among the regions was strengthened. The inter-regional integration of traditional industries, including inter-regional production transfer, enterprise merger, and asset restructuring can promote the vertical, horizontal, and composite extension of the industrial chains [61]. It also motivated expansion of high-order cycles across multiregions, combining adjustment of industrial structure with their respective comparative advantages in the regions of the MLYR. Besides, path diversification in networks can be used to select multiple paths between a given node pair to achieve maximum flow robustness, and the greater the number of paths is, the higher the path connectivity between the two nodes is [62]. So promotion of the interconnection of infrastructure and open platforms was also an important way to increase the quantity and influence of cycles in neighboring regions in the MLYR. (b) The middle-order cycles ($\text{cycle length} \in (7, 15)$) in the ICN were mainly industrial cycles within a province, with its quantity unevenly changed, influence enhanced but vitality inhibited considerably. The CF of middle-order cycles increased in some lengths and decreased in others, which was reflected in the adjustment of the inner industrial chains of some regions such as Shandong and Shaanxi. Reducing overcapacity, and ineffective and low-end supply, closing zombie enterprises, and expanding effective and high-end supply had broken or rebuilt the industrial chains within provinces and profited restructuring of industrial circular chains with medium length. The AD of middle-order cycles showed a gentle upward trend, indicating that effect of promoting the reorganization of industrial chains was highlighted. However, the AI of the middle-order cycles showed a downward trend. Economic trade and relationship are more active when the partners had a high level of R&D expenditures [63]. It can be seen that the utilization of technological resources in the inner-regional circular industrial chains was limited, and the technological investment in high-end manufacturing sectors was relatively weak in some regions such as Inner Mongolia, Shaanxi, and Shanxi of the MLYR. (c) The low-order cycles ($\text{cycle length} \in [2, 7]$) in the ICN with weaker robustness and multiple feedbacks were generally distributed on intersections of industrial chains among new emerging industries, and its influence increased, but quantity and activity greatly decreased. The centrality measure for individual cycles, that is the AD, successfully applied in biological network and real-estate industry network, means that when a cycle intersects an important proportion of all the flows on the network, it is central and influential [50]. As for ICN in the MLYR, the AD of the low-order cycles showed an upward trend, indicating that the role of new emerging industry in leading and driving the industrial economic circulation was being increasing. Development of new low pollution and energy-consuming circular industries can effectively promote the quantity of low-order cycles in the MLYR. However, the CF of low-order cycles declined, and also, the AI of the low-order cycles showed a fluctuating downward trend. The change was reflected in reduction of interindustrial circles across manufacturing and service sectors, and weak investment and consumption demand for emerging services such as cultural tourism, ecological leisure, and health-care sectors.

*3.4. Analysis of Inter-Regional Circulation Effect.* The technology spillover and technology absorption intensity between the five regions of MLYR in 2012 and 2017 are shown in Figure 4. On the whole, the gap between input and output flow was reduced, and economic outflow and inflow become more balanced. The economic complementarities of provinces had been revealed, supported by multilevel economic reform policies. However, the external inter-regional

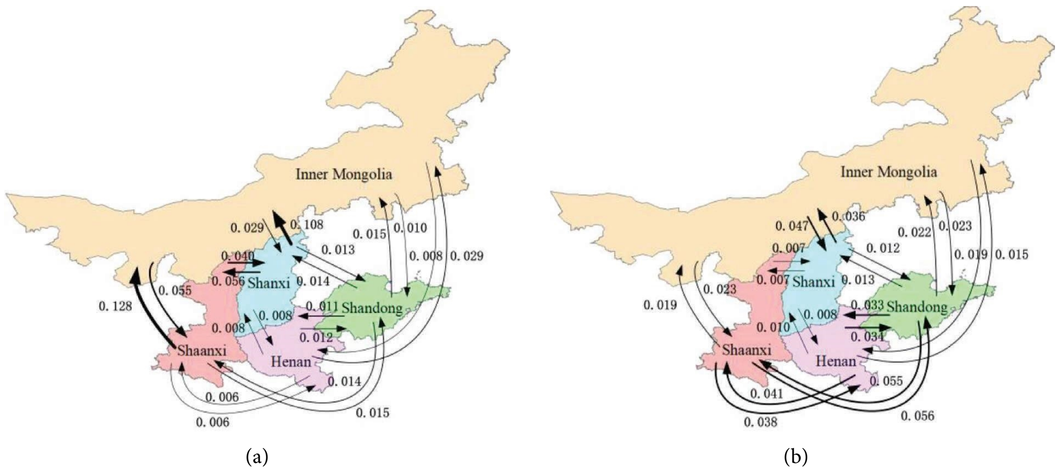



Figure 4: The inter-regional circulation effect of 2012 and 2017. (a) 2012. (b) 2017.

circulation capacity of the provinces was more differentiated. (a) The relatively developed regions in the MLYR with complete industrial system were more interactive, gradually forming a closed loop. As for enhancement of the inter-provincial circulation capacity of industries, circular effects among Shaanxi, Henan, and Shandong, and vitality and influence of the middle-order cycles of these three provinces, whose industrial chains were reorganized effectively, had been considerably improved. Interaction among the three regions was prominent, making the cycles of level-3 enhanced, and the number of cross-provincial high-order cycles increased in some degree. The flow between Henan and Shaanxi in 2017 reached more than six times that of 2012, and economic interaction effect between Shandong and Henan increased. These regions had relatively developed and unified markets, and the decision-making information was more sufficient. Relying on competitive advantages in the industrial chain, economic entities had stronger motivation and awareness to expand the market relationships of upstream and downstream partners. (b) Some regions were still trapped in “resources curse,” and their relations with the external economy were single and weak. Inner Mongolia’s outflow had increased, while the inflow had decreased and the total flow of Shanxi had declined. As for considerably reduction of the level-4 and level-5 of cycles, economic interaction of the developed regions with Inner Mongolia and Shanxi was still weak, and the industrial circular path covering four and five provinces had not yet been unblocked. Besides, the effect of circulation flow between Shanxi and the surrounding regions was reduced, which was related to decrease in the number of low-order cycles. The weak flow of regional economic flow in Shanxi shows that the development and transformation of its resource utilization mode were at a standstill, and the resource dependence had the most typical backbiting effect. Dependence of economic growth on resource industry in Shanxi was not a positive linear relationship. When the threshold value was exceeded, the increase of resource exploitation intensity can restrict the regional economic growth and produce the “resource curse” effect [64], which refers to that the rich natural resources do not significantly promote the economic development, but rather show a blocking effect, which makes the regional industrial structure become rigid and unbalanced [65, 66]. In all, it can be seen that the gradient difference in economic cooperation among the developed regions, such as Shandong and Henan, and the underdeveloped regions, such as Shanxi, was very obvious in the MLYR. Taking the innovation cooperation in Beijing-Tianjin-Hebei as an example, Zhuang discussed the tendency of cooperation among regions and also found that the relationship among developed regions was relatively close, while the relationship between developed regions and underdeveloped regions was relatively loose [67]. So was those characteristic of regional development in the MLYR.

## 4. Conclusions and Suggestions

To solve the imbalance, incoordination, and inter-regional economic segmentation of the MLYR, which can hinder the achievement of sustainable development of the Yellow River basin, from the perspective of optimization of regional economic circulation, we proposed a systematic framework for structural analysis of circular economy and applied it in analysis of economic circulation of the MLYR. Firstly, we defined the inter-regional industrial circular network and propose the construction method of inter-regional industrial circular network. Secondly, we designed indicators such as network, cycle, and inter-regional circulation effects to measure evolution characteristics of the industrial circular network structure. Thirdly, the methods and indicators were applied to explore the structural factors, revealing how the economic circulation was hindered and imbalance of development happened in the MLYR and verified in the empirical research, providing a basis for the government to formulate corresponding industrial policies. We found that the structure of industrial circular network in the MLYR had evolved to a relatively advanced and complex stage. Compared with ICN-2012, the scope of inter-regional and interindustrial circulation was greatly expanded, and the quality and growth of circular economy had been effectively improved, and the effect of internal circulation within regions was strengthened in ICN-2017. The economic complementarities of provinces had been obviously revealed, supported by multilevel economic reform policies. Especially, the inter-regional integration and restructuring of traditional industries resulted in expansion of high-order cycles across multiregions, and strengthening inner-regional industrial circular chains with medium length. However, the external inter-regional circulation capacity of the provinces was more differentiated. It can be seen that the relatively developed regions in the MLYR with complete industrial system were more interactive, gradually forming a closed loop, and some regions were still trapped in "the curse of resources," and their relations with the external economy were single and weak. Limitation of inter-regional capital flow and utilization of technological resources, and weak investment and consumption demand for emerging services inhabited the quantity and activity of low-order cycles, which can result in the imbalance of regional development in the MLYR.

Some suggestions are as follows. Firstly, we should promote the deep integration of the industrial chain and innovation chain in the MLYR and the sharing and transformation of inter-regional scientific and technological resources, and construction of science centers, technology transfer and transformation platforms, and technology innovation centers, improving the open sharing of scientific and technological resources such as large devices, instruments, and talents. We can strengthen the joint participation of universities, research institutions, enterprises, and governments, in establishing industrial technology innovation alliances and accelerating the research and development of key common technologies. Based on information technology, it is possible to update instruments and equipment, improve production processes, enhance the penetration of big data, artificial intelligence, and the Internet of Things into traditional industries, and promote the intelligent upgrading and digital transformation of light industries. Secondly, we should strengthen the cooperation between financial institutions and enterprises and establish a unified and open financial system in the MLYR. A cross-regional financial center can promote the effective connection between high-end financial resources and financing needs of industries, eliminate the restrictions of inter-regional and institutional segmentation, and increase investment for key areas such as industrial technology transfer, traditional industrial transformation, and development of new merging industry. The green financial product system, such as green funds, securities, and insurance, should be focused on, and we can encourage more social capital to participate in green investment and financing by means of subsidy and tax reduction. Thirdly, we should accelerate the green and low-carbon transformation of industries. We can carry out energy conservation, pollution reduction, and carbon reduction, accelerate the ultralow carbon emission transformation of steel, coal, and electricity, and achieve cleaner production in traditional high pollution industries such as metallurgy, coal, chemical industry, building materials. We should cultivate new green low-carbon industries, such as new materials, new energy, characteristic agriculture, cultural tourism, medical care, and health care and also promote the extension of new energy industry chains in the MLYR to the upstream and the downstream, focusing on building wind energy, photovoltaic, hydrogen energy, and energy storage industry clusters, and give priority to hydrogen application in the MLYR.

Based on the existing achievements, the carbon energy cycle network system can be further explored in the future to reveal the feedback and diffusion effects of energy and carbon flow in the cycle system. In addition, we can explore how the controller can operate effectively based on network simulation technology to promote the synchronization and coordination of the circulation network, and control mechanism to generate cooperative behaviors and optimize allocation of resource [68, 69].

## Data Availability

The original data used in this study are from the input-output tables of China released by the National Bureau of Statistics of China in 2012 and 2017. The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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